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Functional Specification

SUPERCONDUCTING BEAM SEPARATION DIPOLES

Abstract

Superconducting beam separation dipoles of four different types are required in the Experimental Insertions (IR 1, 2, 5 and 8) and the RF Insertion (IR 4). Single aperture (D1) and twin aperture (D2) dipoles are utilised in the Experimental Insertions to bring the beams into collision, and two types of twin aperture dipoles (D3 and D4) are used in the RF Insertion to separate the beams more widely as required for the installation of the RF accelerating equipment. These magnets will be delivered in cryo-assemblies known as LBX, LBRA, LBRB, LBRC and LBRS. Under the auspices of the US LHC Accelerator Project, the required magnets will be built at Brookhaven National Laboratory. This specification establishes the functional requirements for the four types of superconducting beam separation dipoles.

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History of Changes

Rev. No.	*Date*	*Pages*	*Description of Changes*
1.0	2000-03-08	All	Initial Submission
1.1	2000-05-30	4 – 9, 25 33	Clarified optics and equipment nomenclature. Changed design pressure to 20 bar. Updated table 11.1.
2.0	2000-06-15	34	Released version.

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1. OVERVIEW

Superconducting beam separation dipoles of four different types are required in the Experimental Insertions (IR 1, 2, 5 and 8) and the RF Insertion (IR 4). Single aperture dipoles (MBX) with lattice designation D1 and twin aperture dipoles (MBRC) with lattice designation D2 are utilised in the Experimental Insertions They bring the two beams of the LHC, separated by 194 mm in the arcs, into collision at four separate points, then separate the beams again beyond the collision point. One side of one such region is shown in Figure 1.1. At the high luminosity insertions IR 1 and 5, a resistive D1 magnet (MBXW) is used due to the large beam losses at that point. The MBXW is outside the scope of this specification. In the RF Insertion two types of twin aperture dipoles, each type with two different aperture spacings are used: D3a and D3b (MBRS) and D4a and D4b (MBRA and MBRB). The D3 and D4 magnets increase the separation of the beams in IR 4 from the nominal spacing of 194 mm to 420 mm so that individual RF cavities can be installed for each beam, and then return the beams to the nominal 194 mm spacing. A drawing of one side of this region is shown in Figure 1.2.

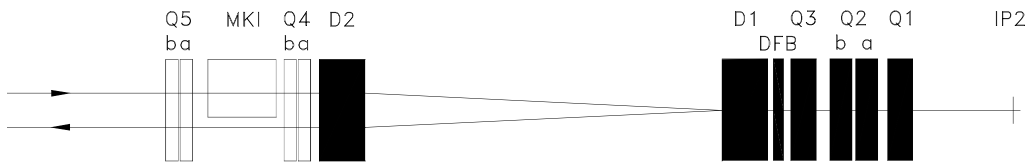

Figure 1.1 Geometry in Intersection Region 2 of the LHC. Dipole magnets D1 and D2 bring the beams into collision at IP2.

Figure 1.2 Geometry in the RF Region of the LHC. The nominal 194 mm separation of the beams in increased to 420 mm so that there is space for independent RF acceleration cavities for the two beams.

Figures 1.3 – 1.6 show cross-sections of the four cryo-assembly types. The D1 magnet will be a single RHIC-type cold mass (MBX) in a LBX cryo-assembly[1]. The D3 magnets will be two single aperture RHIC-type cold masses (MBRS) in a single LBRS cryo-assembly. The D2 (MBRC) and D4 (MBRA and MBRB) magnets will be 2-in-1 cold masses in cryo-assemblies LBRC, LBRA and LBRB respectively. Complete technical descriptions of these magnets are presented in [2].

The dipole magnets are designed with a common element: superconducting coils that are mechanically the same as those built for the RHIC arc dipole magnets [1,3]. The RHIC dipole is a well understood magnet with good quench performance and field quality. The D1 magnets are designed with one RHIC-style cold mass in a RHIC-style cryostat and the D3 magnets are designed with two such cold masses side-by-side in a common cryostat. The cold masses are built straight, without the 47 mm sagitta of the RHIC magnets. The D2 and the D4 magnets are built with coils that are prestressed with stainless steel collars. These collared coils are assembled into yokes with common outside dimensions but with varying internal features (iron saturation control holes, aperture spacing) depending on location. The D2, D3 and D4 magnets utilise a cryostat based on the design used for the LHC arc dipoles[4,5].

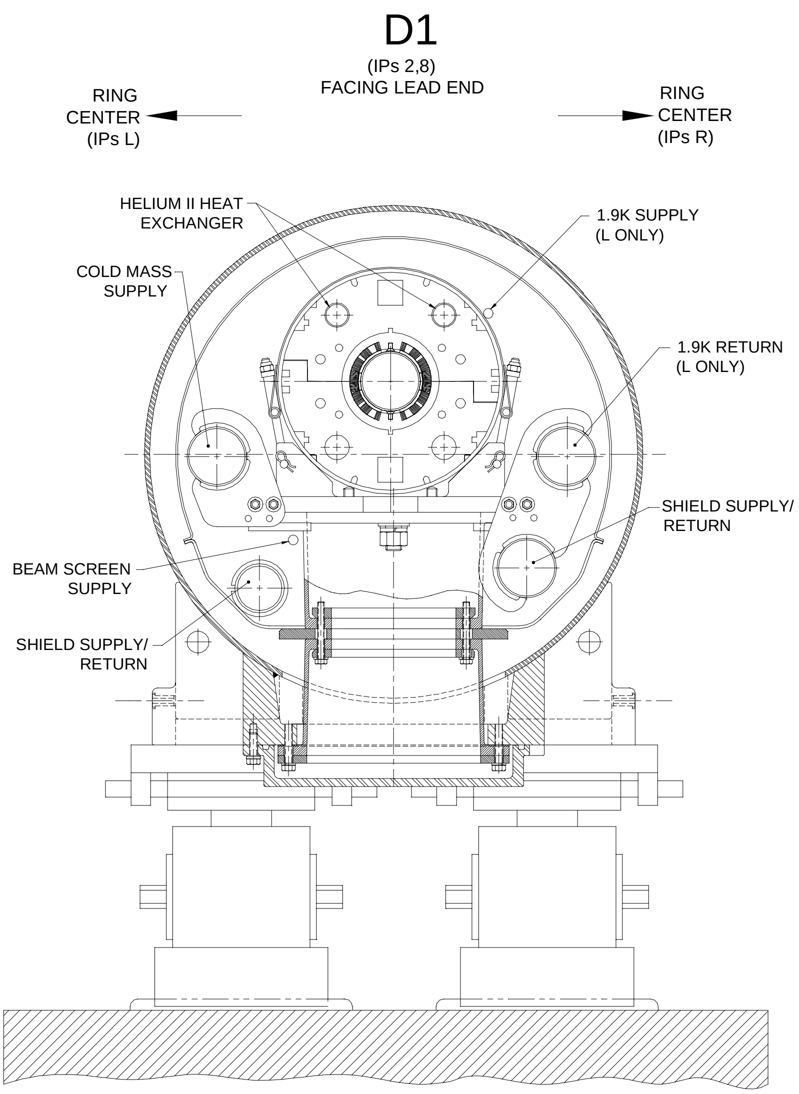

Figure 1.3 Cross Section of the LBX cryo-assembly, facing the lead end of the MBX (D1) magnet. The LBX cryo-assemblies are located on both sides of IP's 2 and 8. Both the cold mass and cryostat are the same design as in RHIC.

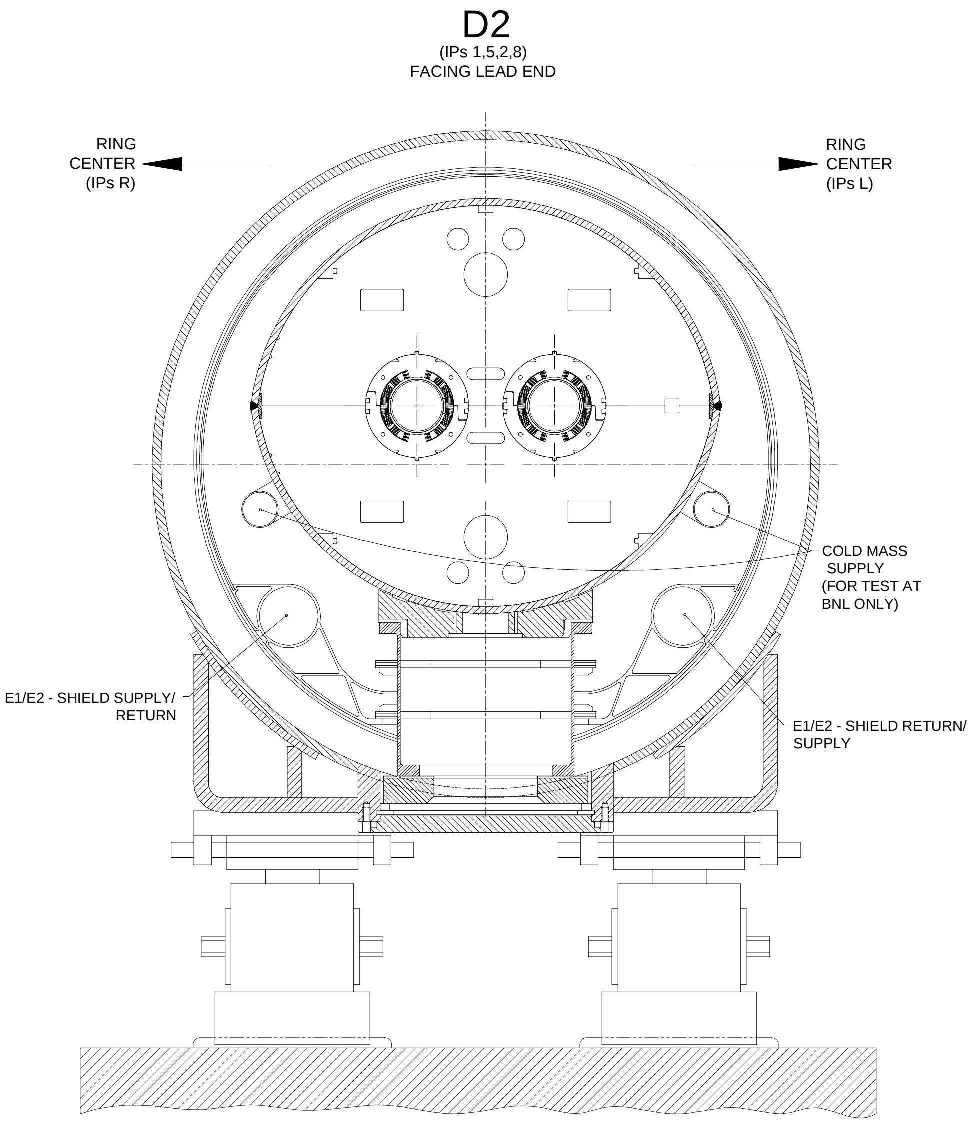

Figure 1.4 Cross Section of the LBRC cryo-assembly, facing the lead end of the MBRC (D2) magnet. LBRC cryo-assemblies are located on both sides of IP's 1, 2, 5, and 8. The cryostat is 914 mm in diameter, the same as the LHC arc. The MBRC is a twin aperture dipole with an aperture spacing of 188 mm.

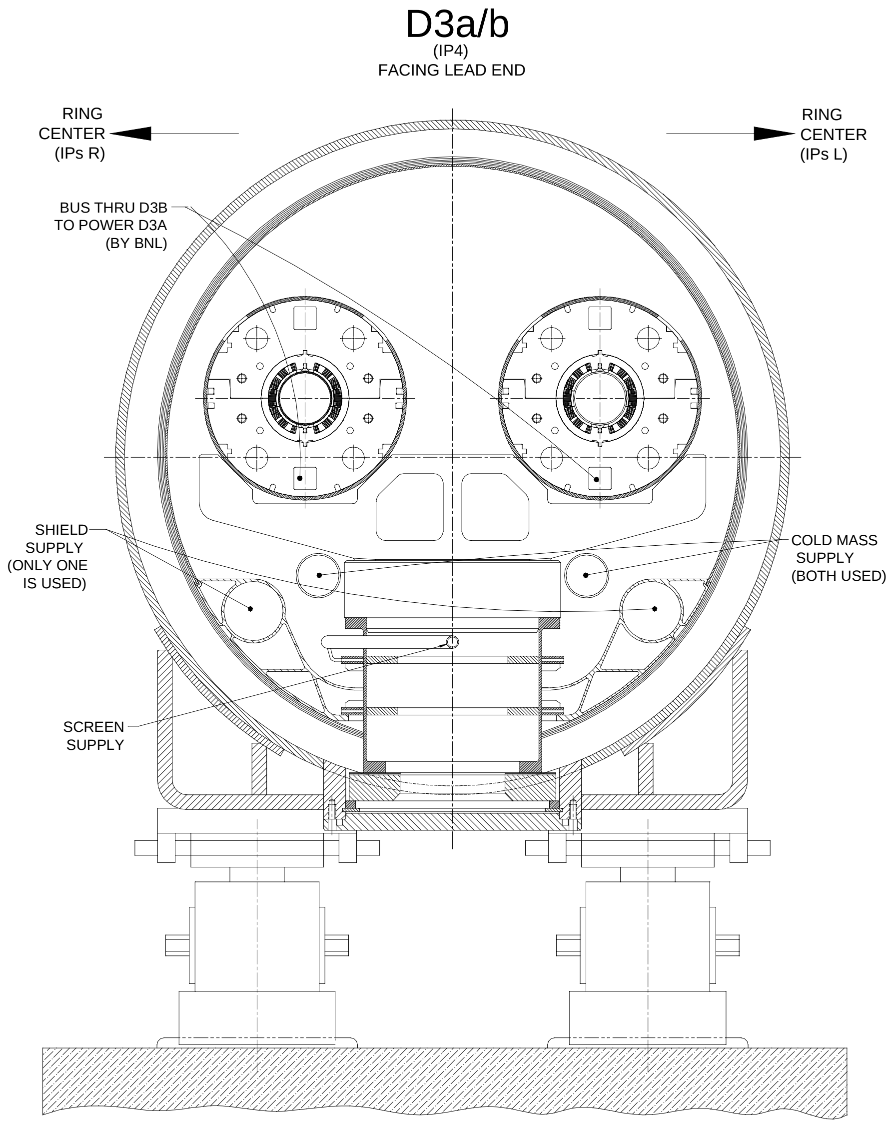

Figure 1.5 Cross Section of the LBRS cryo-assembly, facing the lead end of the MBRS (D3) magnets. The cryostat is 914 mm in diameter, the same as in the LHC arc. Assemblies LBRSA and LBRSB are D3a optical elements with the MBRS apertures spaced 420 mm apart. Assemblies LBRSB and LBRSD are D3b optical elements with the MBRS apertures spaced 382 mm apart.

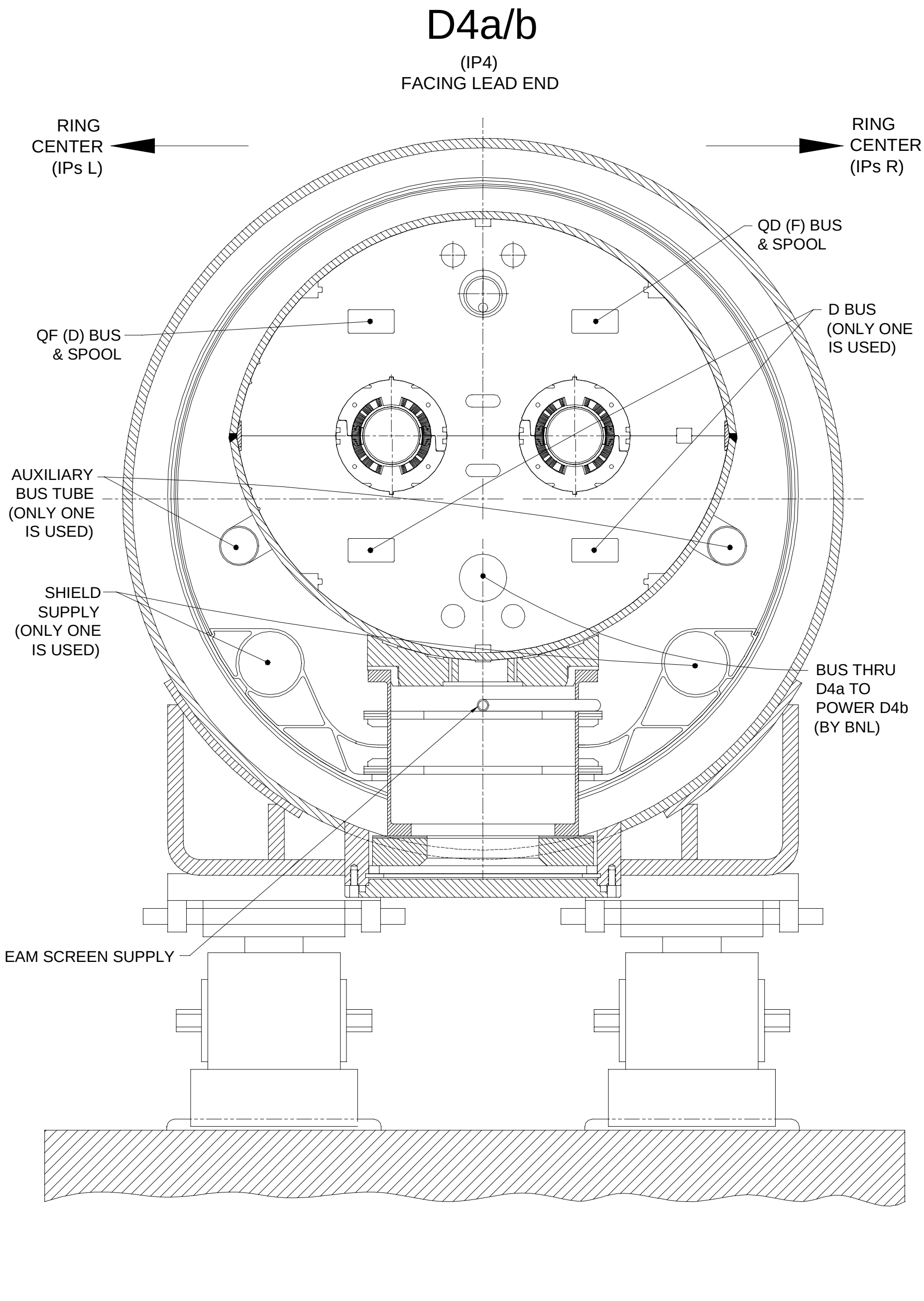

Figure 1.6 Cross Section of the lead end of the LBRA cryo-assembly with the MBRA (D4a) magnet or the LBRB cryo-assembly with the MBRB (D4b) magnet. There is an LBRA and an LBRB cryo-assembly on each side of IP 4. The cryostat is 914 mm in diameter, the same as in the LHC arc. The MBRA (D4a) aperture separation is 232 mm. The MBRB (D4b) aperture separation is 194 mm. A substantial amount of bus work that services the magnets in the adjacent LHC arc passes through the D4 magnets.

2. LATTICE REQUIREMENTS

The beam separation dipoles serve to move the beams from the standard spacing of 194 mm in the arcs either into a common channel to be brought into collision at the experimental insertions or to a wider separation of 420 mm in the RF insertion at IR4, and then to return the beams to the 194 mm spacing on the other side of the long straight section. This requires single and twin-aperture magnets with several aperture spacings.

Table 2.1 summarises the types, number and locations of the various magnet required. In the remainder of this document magnets will be referred to by their optics designation; in all cases these references will designate the magnet and cryo-assembly types specified in Table 2.1 and shown in Figures 1.3 – 1.6.

The lattice location of each magnet is specified in drawings LHCLSXG_0001 (IR 1, 2, 3, and 4) and LHCSXG_0003 (IR 5,6,7, and 8) for version 6.1 of the LHC optics. The locations of the beam separation dipoles are summarised in Table 2.2 and shown in detail in Figures 2.1 – 2.7, which are taken from the V6.1 lattice drawings.

Table 2.1 Superconducting beam separation dipole parameters. All magnets have a coil aperture of 80 mm and a magnetic length of 9.45 m.

Optics Name	*IR Location*	*Magnet Code*	*Style*	*Cryo-Assembly Code*	*No.*	*Spare*	*Aper. Sep. (cold) mm*	*Oper. Temp., K*
D1	IR2, IR8	MBX	Single Aperture	LBX	4	1	---	1.9
D2	IR1, IR2, IR5, IR8	MBRC	2-in-1	LBRC	8	1	188	4.5
D3a	IR4	MBRS	Dual 1-in-1	LBRSA[1] LBRSC	2	1	420	4.5
D3b	IR4	MBRS	Dual 1-in-1	LBRSB[2] LBRSD	2	1	382	4.5
D4a	IR4	MBRA	2-in-1	LBRA	2	1	232	1.9
D4b	IR4	MBRB	2-in-1	LBRB	2	1	194	1.9

Note 1: LBRSA and LBRSC cryo-assemblies are designed to be interchangeable. A total of three, including a spare, will be built. LBRSA goes on the left side of IP4 and LBRSC goes on the right side of IP4.

Note 2: LBRSB and LBRSD cryo-assemblies are designed to be interchangeable. A total of three, including a spare, will be built. LBRSB goes on the left side of IR4 and LBRSD goes on the right side of IP4.

Table 2.2 Lattice locations of the separation dipoles. The distance from the IP is measured to the beginning of the magnetic length. The slot length is between virtual mid-planes of the interconnects. All dipoles have a magnetic length of 9.45 m.

Name	***IP***	***Distance From IP, m***	***Slot Length, M***
D1	IR 2 and 8	58.383	10.983
D2	IR 2 and 8	121.476	11.718
D2	IR 1 and 5	153.479	11.718
D3a	IR 4 left	200.317	10.746
D3b	IR 4 left	211.063	11.358
D4a	IR 4 left	242.023	11.478
D4b	IR 4 left	252.889	10.866
D3a	IR 4 right	201.224	10.746
D3b	IR 4 right	211.970	11.358
D4a	IR 4 right	242.046	11.478
D4b	IR 4 right	252.912	10.866

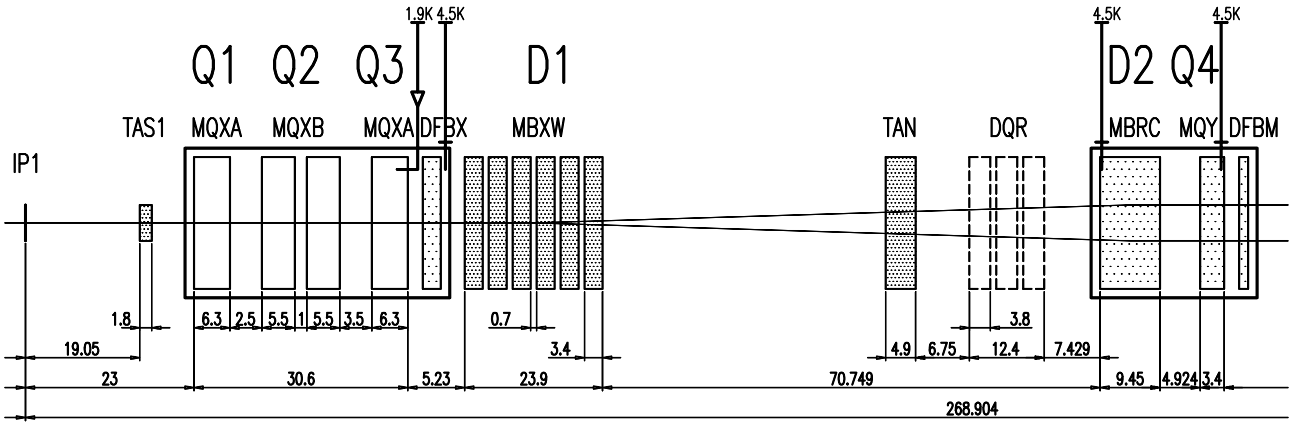

Figure 2.1 Lattice layout for the right side of IR 1. The positions of the magnets on the left side are mirror-symmetric with those on the right, and the positions of magnets are the same at IR 5 as at IR 1.

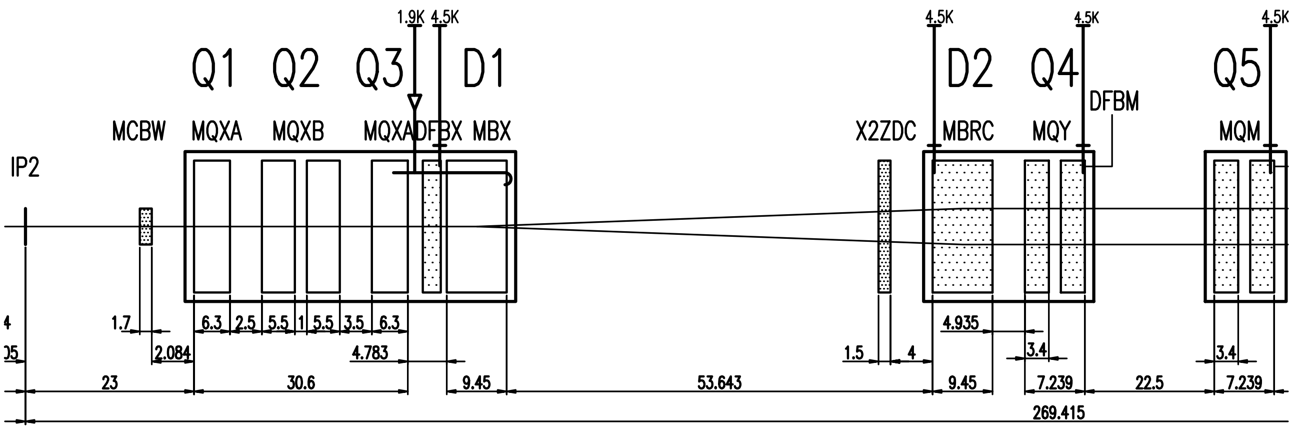

Figure 2.2 Lattice layout for the right side of IR 2. The positions of the magnets on the left side are mirror-symmetric with those on the right.

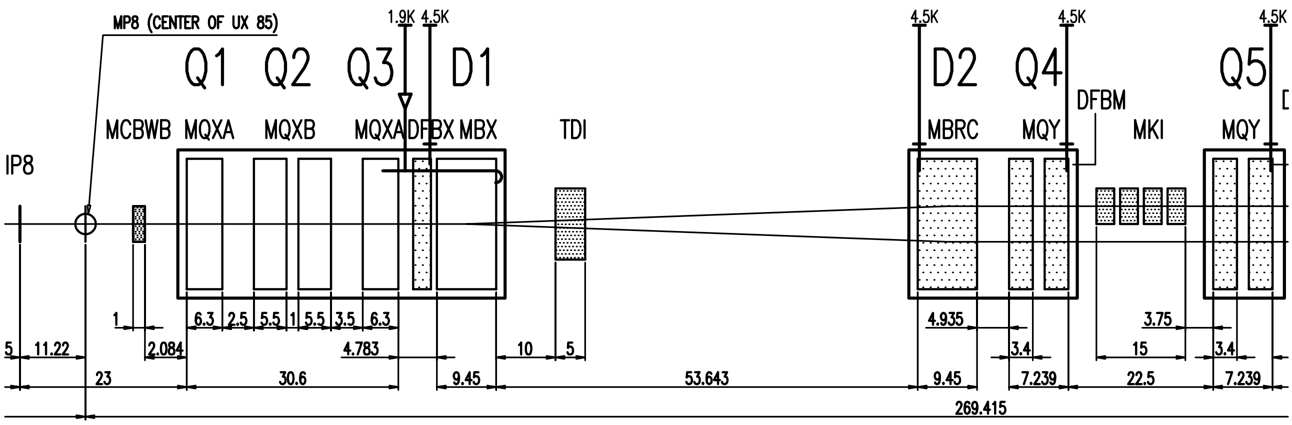

Figure 2.3 Lattice layout for the right side of IR 8. The positions of the magnets on the left side are mirror-symmetric about IP8 with those shown on the right.

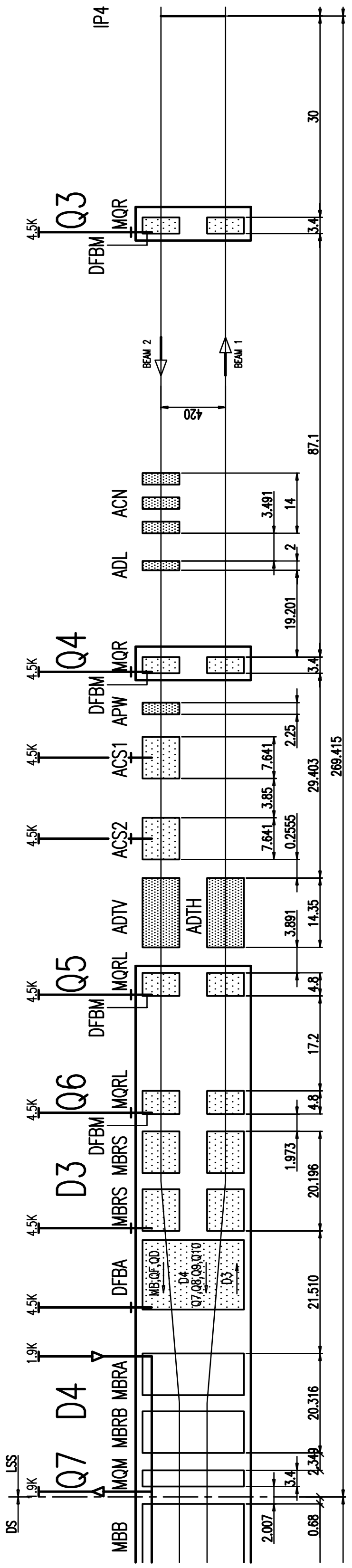

Figure 2.4 Lattice layout for IR4 left.

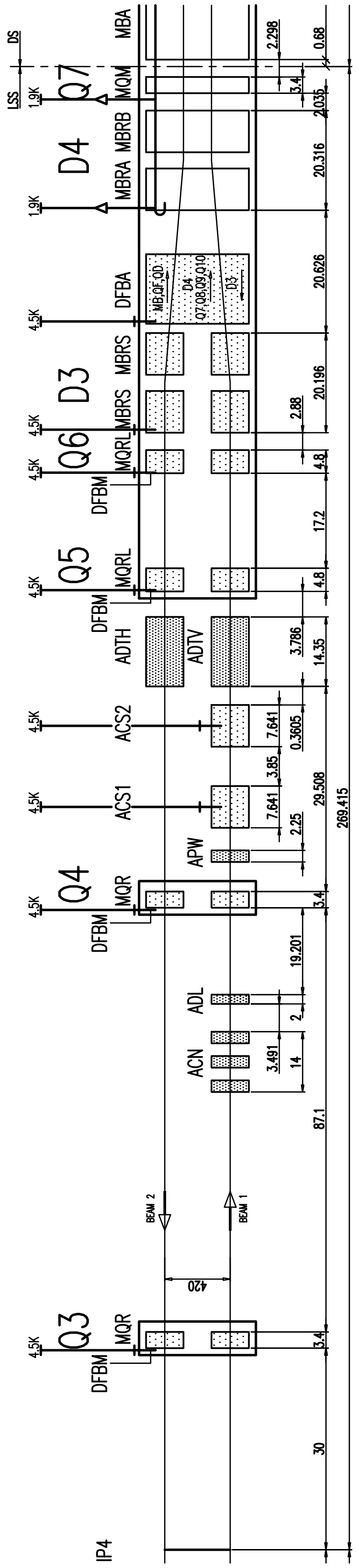

Figure 2.5 Lattice layout for IR4 right.

3. MAGNETIC REQUIREMENTS

3.1 FIELD STRENGTH

The required field strength depends on the distance between bend centres and the beam offset produced by pairs of dipoles, and this varies from location to location. Table 3.1 summarises the field strengths required at injection (0.45 TeV), collision (7 TeV) and ultimate (7.54 TeV) beam energy.

The different dipole types require different currents to reach the same field. The principal difference is between the single-aperture (D1 and D3) and twin-aperture (D2 and D4) cold masses. Table 3.2 lists operating parameters of the D4b magnet near the operating field. Figure 3.1 shows the transfer function of the D4b dipole as a function of excitation current. Figure 3.2 displays the field versus current relation for all magnet types, and figure 3.3 plots the current difference relative to D3a required to reach a particular field.

Table 3.1 Position parameters and fields required in the magnets at injection energy, nominal energy, and ultimate energy, corresponding to lattice version 6.1. The magnetic length of the magnets is 9.45 m.

Magnet	*IR Location*	*Bend Centre-to-Centre, m*	*Deflection, m*	*Field (T) for E (TeV)*		
				0.45	***7.0***	***7.54***
D1/D2	1 & 5	87.424	0.097	0.176	2.742	2.954
D1/D2	2 & 8	63.093	0.097	0.244	3.799	4.093
D3/D4	4 left	41.766	0.113	0.215	3.343	3.602
D3/D4	4 right	40.882	0.113	0.220	3.415	3.680

Table 3.2 Typical operating parameters for the D4b dipole.

Item	*Value*
Magnetic length	9.45 m
Integral field, magnet-to-magnet variation, rms	5×10^{-4}
Current at injection field (0.215 T)	340 A
Current at operating field (3.343 T)	5280 A
Quench current at 4.5K	7740 A
Quench field at 4.5 K	4.8 T
Inductance of each aperture	25.8 mH
Stored energy in each aperture at 3.343 T	360 kJ

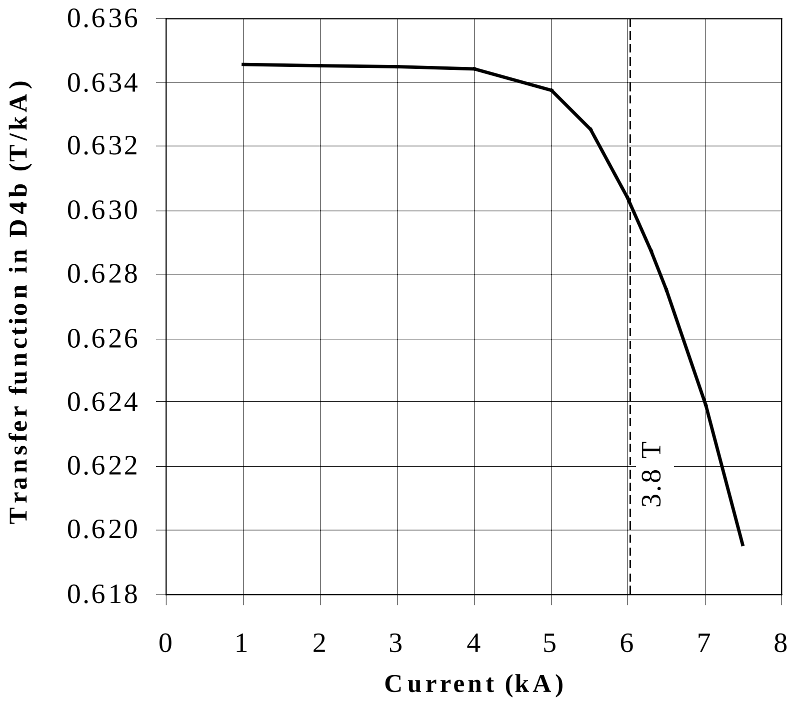

Figure 3.1 Transfer function of 2-in-1 dipole D4b

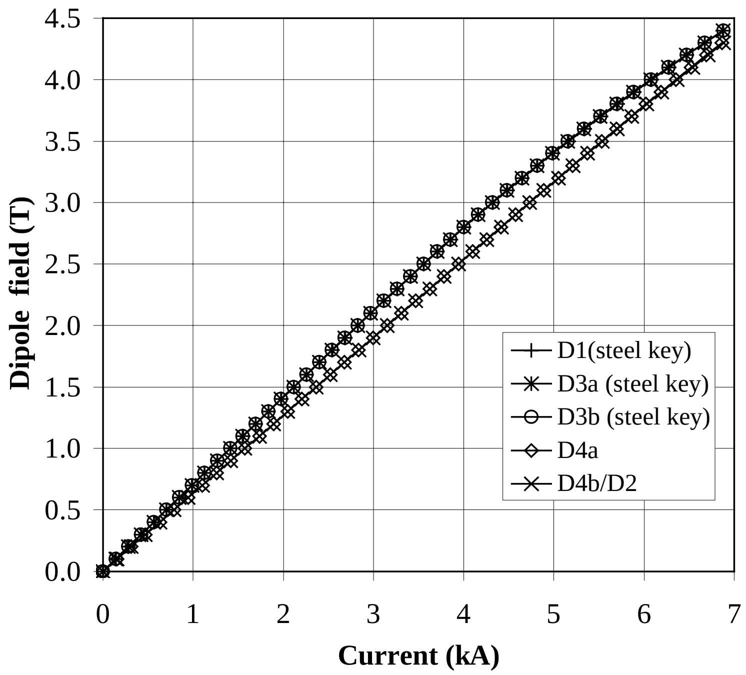

Figure 3.2 Field versus current for all magnet types.

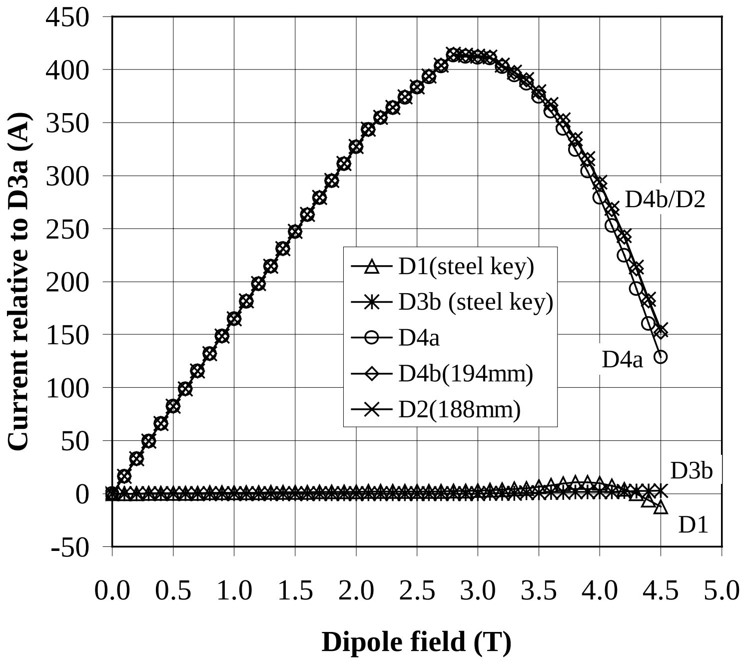

Figure 3.3 Current relative to D3a for a particular field in the various magnets

3.2 FIELD QUALITY

The expected field quality of superconducting magnets is characterised by reference tables showing the expected mean value ($<b_n>$ or $<a_n>$), uncertainty in the mean (Δb_n or Δa_n), and rms variation about the mean ($\sigma(b_n)$ or $\sigma(a_n)$) of the field harmonics. Calculations [6] of the expected harmonics in the superconducting beam separation dipoles have been done based on the extensive experience with RHIC dipoles. The RHIC data apply directly to the D1 and D3 magnets, which are based on RHIC-type cold masses. Adjustments to the expected mean values are made for the D2 and D4 dipoles, which use RHIC-type coils but with stainless steel collars and a common yoke for the two apertures, based on magnetic design calculations[7].

The reference harmonics tables are shown in Tables 3.3 – 3.5 for fields of 0.2 T, 3.55 T and 3.8 T. Table 3.3 shows the expected field errors for D1 and D3, which both use RHIC-type cold masses. Table 3.4 gives the harmonics for D4a. A common error table (Table 3.5) is used for D4b and D2, since the aperture spacing is very similar for the two types.

The field quality given in Tables 3.3 – 3.5 has been shown to be suitable for the LHC for nominal proton and heavy ion operation, both for injection and for collision lattices. Beam dynamics and tracking studies have been carried out as part of the US/CERN collaboration [8]. In these studies, both the dynamic aperture and the tune footprint were used as quantities to evaluate the impact of magnet errors.

Table 3.3 Reference harmonics table V1.0 for D1 and D3 dipoles, integrated over the full length of the magnet body plus ends, at a reference radius of 17 mm.

D1, D3 at 0.2 T

n	*<b>*	*Δb*	*σ(b)*	*<a>*	*Δa*	*σ(a)*
2	0.07	0.52	0.19	-0.06	2.50	1.04
3	-5.21	2.55	0.90	-0.51	0.23	0.08
4	-0.02	0.06	0.03	0.04	0.36	0.13
5	0.13	0.18	0.09	0.04	0.03	0.01
6	-0.001	0.012	0.004	-0.004	0.079	0.022
7	-0.027	0.021	0.010	-0.009	0.007	0.002
8	-0.002	0.002	0.001	-0.001	0.010	0.003
9	0.006	0.006	0.002	0.001	0.001	0.000
10	0.001	0.002	0.001	0.001	0.002	0.001
11	-0.014	0.001	0.000	0.000	0.000	0.000

D1, D3 at 3.55 T

n	*<b>*	*Δb*	*σ(b)*	*<a>*	*Δa*	*σ(a)*
2	0.05	0.54	0.19	0.39	2.52	1.03
3	-0.13	1.65	0.79	-0.59	0.25	0.08
4	0.00	0.07	0.03	0.02	0.34	0.13
5	0.10	0.17	0.08	0.04	0.04	0.01
6	-0.019	0.015	0.006	-0.007	0.080	0.023
7	0.122	0.019	0.010	-0.011	0.006	0.002
8	-0.001	0.002	0.001	-0.001	0.010	0.003
9	0.000	0.005	0.002	0.000	0.001	0.000
10	0.001	0.002	0.001	0.001	0.001	0.001
11	-0.012	0.001	0.000	0.000	0.000	0.000

D1, D3 at 3.8 T

n	*<b>*	*Δb*	*σ(b)*	*<a>*	*Δa*	*σ(a)*
2	0.17	0.54	0.19	0.37	2.52	1.03
3	-0.79	1.65	0.79	-0.61	0.25	0.08
4	0.02	0.07	0.03	0.02	0.34	0.13
5	0.05	0.17	0.08	0.03	0.04	0.01
6	-0.017	0.015	0.006	-0.007	0.080	0.023
7	0.116	0.019	0.010	-0.011	0.006	0.002
8	-0.001	0.002	0.001	-0.001	0.010	0.003
9	0.000	0.005	0.002	0.000	0.001	0.000
10	0.001	0.002	0.001	0.001	0.001	0.001
11	-0.013	0.001	0.000	0.000	0.000	0.000

Table 3.4 Reference harmonics table V1.0 for D4a dipoles, integrated over the full length of the magnet body plus ends, at a reference radius of 17 mm.

D4a at 0.2 T

n	<*b*>	Δ*b*	σ(*b*)	<*a*>	Δ*a*	σ(*a*)
2	0.05	0.52	0.19	-0.06	2.50	1.04
3	-4.59	2.55	0.90	-0.51	0.23	0.08
4	-0.02	0.06	0.03	0.04	0.36	0.13
5	0.14	0.18	0.09	0.04	0.03	0.01
6	-0.001	0.012	0.004	-0.004	0.079	0.022
7	-0.026	0.021	0.010	-0.009	0.007	0.002
8	-0.002	0.002	0.001	-0.001	0.010	0.003
9	0.006	0.006	0.002	0.001	0.001	0.000
10	0.001	0.002	0.001	0.001	0.002	0.001
11	-0.014	0.001	0.000	0.000	0.000	0.000

D4a at 3.55 T

n	<*b*>	Δ*b*	σ(*b*)	<*a*>	Δ*a*	σ(*a*)
2	0.05	0.54	0.19	0.37	2.52	1.03
3	1.01	1.65	0.79	-0.49	0.25	0.08
4	-0.01	0.07	0.03	0.02	0.34	0.13
5	0.03	0.17	0.08	0.04	0.04	0.01
6	0.000	0.015	0.006	0.000	0.080	0.023
7	0.002	0.019	0.010	-0.011	0.006	0.002
8	-0.001	0.002	0.001	-0.001	0.010	0.003
9	0.000	0.005	0.002	0.000	0.001	0.000
10	0.001	0.002	0.001	0.001	0.001	0.001
11	-0.012	0.001	0.000	0.000	0.000	0.000

D4a at 3.8 T

n	<*b*>	Δ*b*	σ(*b*)	<*a*>	Δ*a*	σ(*a*)
2	0.03	0.54	0.19	0.37	2.52	1.03
3	1.06	1.65	0.79	-0.49	0.25	0.08
4	-0.02	0.07	0.03	0.02	0.34	0.13
5	-0.02	0.17	0.08	0.04	0.04	0.01
6	-0.001	0.015	0.006	0.000	0.080	0.023
7	0.004	0.019	0.010	-0.011	0.006	0.002
8	-0.001	0.002	0.001	-0.001	0.010	0.003
9	0.000	0.005	0.002	0.000	0.001	0.000
10	0.001	0.002	0.001	0.001	0.001	0.001
11	-0.012	0.001	0.000	0.000	0.000	0.000

Table 3.5 Reference harmonics table V1.0 for D2 and D4b dipoles, integrated over the full length of the magnet body plus ends, at a reference radius of 17 mm.

D4b, D2 at 0.2 T

n	*<b>*	*Δb*	*σ(b)*	*<a>*	*Δa*	*σ(a)*
2	0.03	0.54	0.19	0.37	2.52	1.04
3	1.06	1.65	0.79	-0.49	0.25	0.08
4	-0.02	0.07	0.03	0.02	0.34	0.13
5	-0.02	0.17	0.08	0.04	0.04	0.01
6	-0.001	0.015	0.006	0.000	0.080	0.023
7	0.004	0.019	0.010	-0.011	0.006	0.002
8	-0.001	0.002	0.001	-0.001	0.010	0.003
9	0.000	0.005	0.002	0.000	0.001	0.000
10	0.001	0.002	0.001	0.001	0.001	0.001
11	-0.012	0.001	0.000	0.000	0.000	0.000

D4b, D2 at 3.55 T

n	*<b>*	*Δb*	*σ(b)*	*<a>*	*Δa*	*σ(a)*
2	0.04	0.54	0.19	0.37	2.52	1.03
3	0.91	1.65	0.79	-0.49	0.25	0.08
4	-0.04	0.07	0.03	0.02	0.34	0.13
5	0.04	0.17	0.08	0.04	0.04	0.01
6	-0.004	0.015	0.006	0.000	0.080	0.023
7	0.002	0.019	0.010	-0.011	0.006	0.002
8	-0.001	0.002	0.001	-0.001	0.010	0.003
9	0.000	0.005	0.002	0.000	0.001	0.000
10	0.001	0.002	0.001	0.001	0.001	0.001
11	-0.012	0.001	0.000	0.000	0.000	0.000

D4b, D2 at 3.8 T

n	*<b>*	*Δb*	*σ(b)*	*<a>*	*Δa*	*σ(a)*
2	-0.05	0.54	0.19	0.37	2.52	1.03
3	0.92	1.65	0.79	-0.49	0.25	0.08
4	-0.07	0.07	0.03	0.02	0.34	0.13
5	0.01	0.17	0.08	0.04	0.04	0.01
6	-0.007	0.015	0.006	0.000	0.080	0.023
7	0.006	0.019	0.010	-0.011	0.006	0.002
8	-0.001	0.002	0.001	-0.001	0.010	0.003
9	0.000	0.005	0.002	0.000	0.001	0.000
10	0.001	0.002	0.001	0.001	0.001	0.001
11	-0.012	0.001	0.000	0.000	0.000	0.000

The mean value of some of the harmonics will change with magnet excitation, due to persistent current in the superconductor and iron saturation. Figure 3.4 shows the measured dependence of the allowed multipoles b_3, b_5, and b_7 in a typical RHIC dipole. Similar behaviour is expected in the D1 and D3 dipoles. The twin-aperture design allows additional harmonics to show systematic variation with field due to iron saturation effects. Due to the different inner diameter of the yoke, the allowed harmonics will display different saturation effects than in the D1 and D3. The expected behaviour in D2 and D4b due to iron effects, based on POISSON calculations, is shown in Figure 3.5. In D4a, the quadrupole, octupole and 12-pole terms will be somewhat smaller due to the larger aperture spacing.

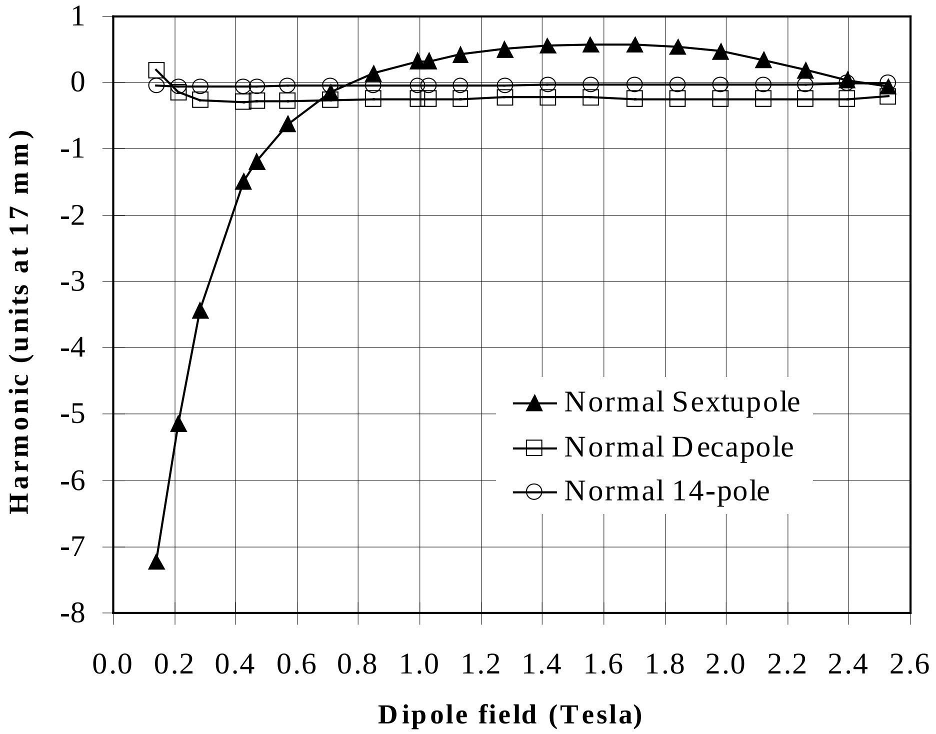

Figure 3.4 The measured dependence of the sextupole, decapole and 14-pole harmonics on field during up-ramp in the 80 mm aperture RHIC arc dipole DRG107. At low fields, the value of the sextupole harmonic (b_3) is dominated by the persistent currents.

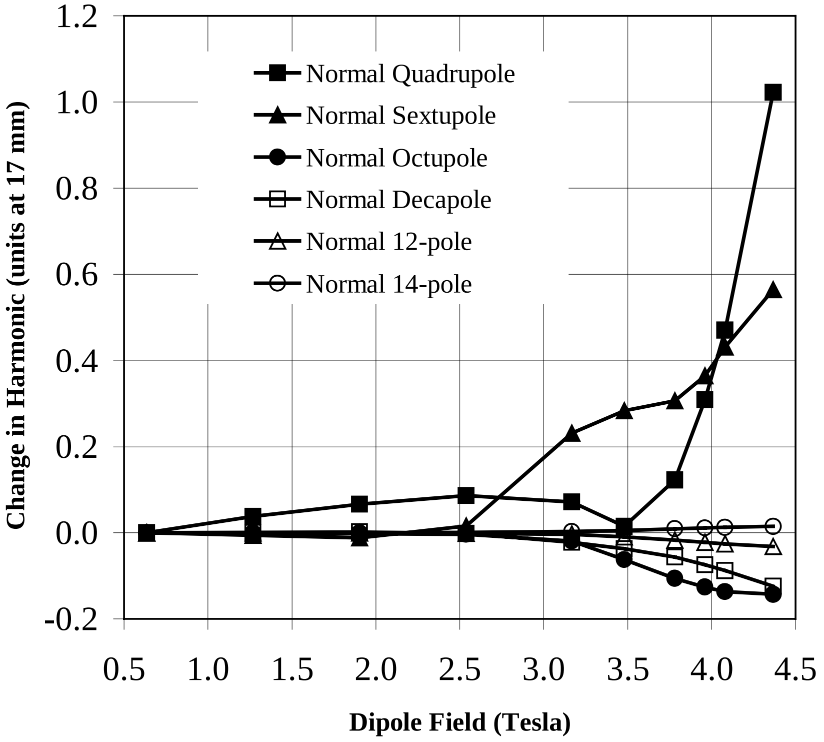

Figure 3.5 The computed current dependence of the field harmonics in an aperture of dipole D2 due to iron saturation effects. The maximum operating field in the magnets is 3.8 T.

3.3 CURRENT IMBALANCE BETWEEN TWO APERTURES

The dipole D2 may be operated with a small current imbalance in one aperture with respect to the other. Figure 3.6 shows the effect of such an imbalance on the fields in the magnet. In these calculations, 15 % additional current is assumed in the left aperture and the field changes in both the left and the right apertures are then plotted as a function of field in the right aperture. The effects for both D4b, which has an aperture separation of 194 mm, and D2, with an aperture separation of 188 mm, are shown and are small. At 4 T, the maximum difference in left/right harmonics is ~ 3 units for the sextupole term. The transfer function difference is less than 0.1 %.

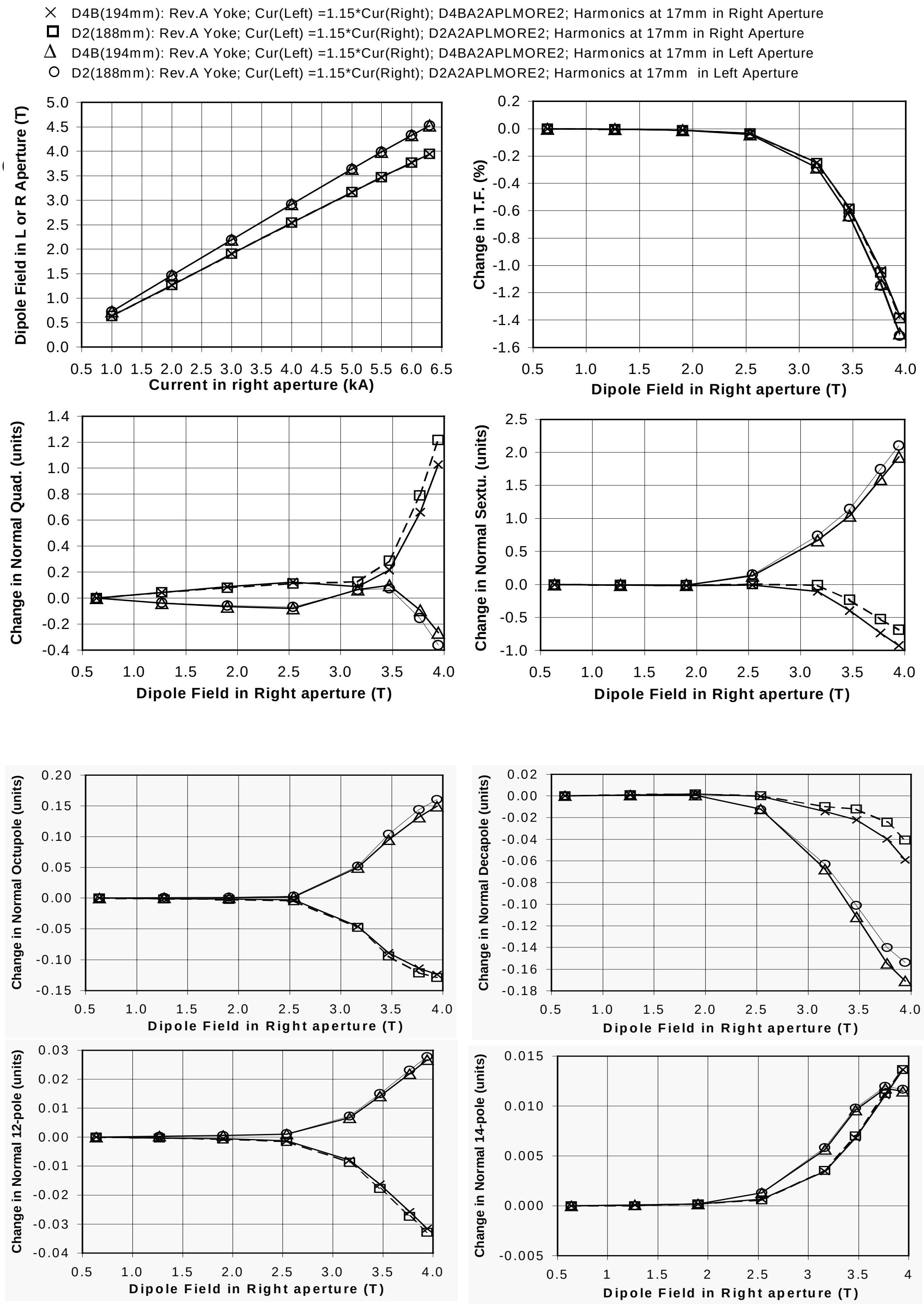

Figure 3.6 Change in harmonics with a 15 % current imbalance in the apertures of the 2-in-1 magnets D2 and D4b.

3.4 FIELD AXIS

Field angle errors, including the average field angle accuracy, rms variation of field angle within one bore, and the rms difference in field angle between the two bores, have been estimated based on RHIC data[1,3] and are summarised in Table 3.6.

Table 3.6 Estimated field angle errors

Item	*Value*
Single magnet, mean dipole angle, α	$\pm$ 3 mrad
Single magnet, variation (twist) of dipole angle $\Delta\alpha$ from mean, rms	2 mrad
Mean angle between apertures, rms	2 mrad

4. ELECTRICAL REQUIREMENTS

4.1 POWER LEADS AND BUSSES

The lead end orientation of all the superconducting beam separation dipoles is mirror-symmetric about the appropriate IP. The orientation of each magnet type is shown in Table 4.1

Table 4.1 Lead end orientation of beam separation dipoles

Magnet	Lead end orientation
D1	Towards IP
D2	Away from IP
D3a and D3b	Away from IP
D4a and D4b	Toward IP

Each single-aperture type magnet (D1 and each aperture of D3), is provided with a pair of power leads made of the same superconducting cable as used in the coils. Each lead will be marked "A" or "B" according to the standard LHC convention[9] such that with current entering the A lead and exiting the B lead an upward dipole field is produced. A bus flex joint assembly will be used in the lead end volume for expansion and contraction of the power bus connected to the adjacent element. D3b will carry a through bus to carry the current to the D3a. The two apertures of each D3 are bussed independently; the series connection between the two channels and provision for trimming one with respect to the other will be done in the DFBA through which they are powered.

Each D2 and D4b magnet will be provided with a pair of main power leads and a centre-tap lead for up to 600 A at the point of connection between the two apertures. The main leads will be marked "A" or "B" according to the standard LHC convention[9] such that with current entering the A lead and exiting the B lead an upward dipole field is produced in both apertures. A bus flex joint assembly will be used in the lead end volume for expansion and contraction of the power bus connected to the adjacent element.

Each D4a magnet will be provided with a pair of main power leads and a centre-tap lead for up to 600 A. A through bus, including the centre tap lead, will be provided to carry power to D4b. The main power leads and the leads from each aperture of D4a will be bussed internally to the lead end volume, as shown in Figure 4.1, to allow each beam channel of the pair to be powered in series with a single centre tap lead for trimming one channel with respect to the other. The main leads will be marked "A" or "B" according to the standard LHC convention[9] such that with current entering the A lead and exiting the B lead an upward dipole field is produced in both apertures. A bus flex joint assembly will be used in the lead end volume for expansion and contraction of the power bus connected to the adjacent element.

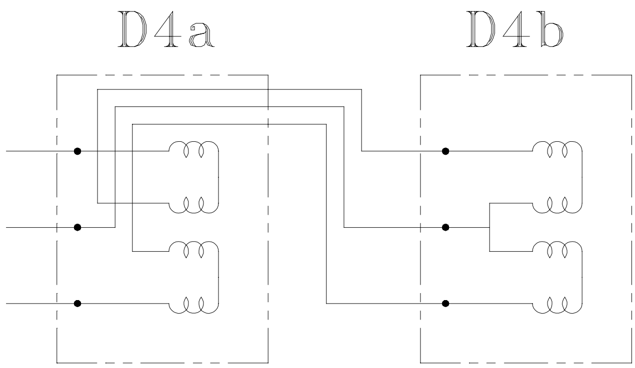

Figure 4.1 Schematic diagram of the powering of D4a and D4b.

Both D4 magnets carry the busses for the magnets in the adjacent arcs. This includes the main dipole and quadrupole busses (13 kA), which pass through the D4 cold mass, and the auxiliary busses (600 A and 6 kA), which pass through an auxiliary tube on the outside of the cold mass. The auxiliary busses will be installed in the tunnel and are not provided with the magnet. Because the D4 lead end orientation is reversed on one side of the IP from the other, while that of the main magnets is always in the same direction, two dipole busses and two auxiliary bus tubes are provided, one or the other of which will be used, depending on the D4 orientation. Similarly, the assignment of focusing and defocusing quadrupole busses will depend on the magnet orientation. Bus flex joint assemblies will be used in the lead end volume for expansion and contraction of each of the main magnet power busses connected to the adjacent element. Bus flex joint assemblies will be provided in both ends of the D4b to allow it to be used in either orientation with respect to the adjacent Q7.

4.2 QUENCH PROTECTION REQUIREMENTS

Redundant voltage taps will be installed across each half coil of the magnets (D1-D4). These allow quenches to be detected via a voltage imbalance between half circuits. Two lead wires will be attached at each tap for redundancy.

Quench protection heaters are used to protect the coils from excessive local energy deposition during a quench. The heaters run the full length of the magnet, one per quadrant, and are installed between the collars/phenolic spacers and coils at the time of coil assembly for collaring. Two independent heater circuits per magnet are included. The heater design is one previously developed at BNL and some modification to standard CERN power supplies may be required for their operation [10]. In the cases where two magnets are powered in series (D3a and D3b, and D4a and D4b), a quench detected in one is intended to cause the heaters in both to be energised, quenching all four apertures. Quench protection diodes are not used in any of these magnets.

4.3 VOLTAGE LIMITS

All components are designed to withstand the maximum voltages which can appear during normal operation, including ramping up, ramping down and quenching. The magnet coils and the quench protection heaters will be tested according to or exceeding the specifications in [11]. The test voltages are summarised in Table 4.2.

Table 4.2 Test voltages for beam separation dipoles.

Component	Test voltage
Coil	5 kV
Quench heaters	5 kV

5. CRYOGENIC REQUIREMENTS

5.1 OPERATING TEMPERATURES

The dipoles will operate either in a static bath of liquid helium at 4.5 K and 1.3 bar, or in a static bath of superfluid helium at 1.9 K and 1.3 bar. Table 5.1 specifies the temperature of each magnet and the local slope. The operating temperature is determined by the logistics of position in the lattice of the LHC. The magnets can provide the required field strength at temperatures somewhat higher than 4.5 K; there is about a 3.5 % reduction in quench field with each 0.1 K temperature rise in this range. Depending on position in the LHC and the operating temperature, provision must be made in the magnets constructed for the correct interfaces, pipes and controls in each magnet.

Table 5.1 Operating temperatures and slopes for each magnet. A positive slope indicates the right side of the IP is higher than the left side.

Item	***Units***	***D1***	***D2***	***D3***	***D4***
Operating Temperature	K	1.9	4.5	4.5	1.9
IR 1 Slope	%		+1.23		
IR 2 Slope	%	+1.39	+1.39		
IR 4 Slope	%			-0.36	-0.36
IR 5 Slope	%		-1.24		
IR 8 Slope	%	+0.36	+0.36		

5.2 COOLING CIRCUITS

Figures 5.1 – 5.4 are schematic diagrams illustrating typical cooling circuits for each of the magnet types. The section of each diagram within the dashed line marked "BNL" specifies the cryogenic piping and connections that are the responsibility of BNL. The remainder of each diagram, showing the connections to adjacent magnets and to the cryogenic transfer line, are included to illustrate the functions of the components within the magnets, but are not themselves part of this specification. The D1 is connected to the cryogenic distribution line through the LBNL-provided DFBX, and the D3 and D4 are connected through CERN provided cryogenic service modules (QQS). The connection from the D2 to the cryogenic distribution line is made through a "mini-QQS," which is an integral part of the D2 cryostat and is provided by BNL. Details of the cooling schemes are presented in [12].

The D2 and D3 magnets, which are cooled with static, pool-boiling liquid helium at 4.5 K and 1.3 bar, must be fitted with vent pipes, liquid fill lines (for steady-state operation) and liquid level sensors at the up-hill end, and with liquid fill lines (for cooldown) at the down-hill end. Since, depending on location, either end of each magnet type may be the up-hill or down-hill end, liquid level probes and fill and vent lines are provided to allow operation with either slope by making the appropriate connections at the time of installation[13].

The D1 and D4 magnets are cooled with static superfluid helium at 1.9 K. Internal heat exchangers are provided to cool the magnets from 4.5 K to 1.9 K. In the case of the D4, a single heat exchanger, identical to that used in the main magnets, is used. For D1, two smaller heat exchangers are installed in the top two 30 mm diameter cooling holes in the yoke. The two heat exchangers and the two liquid fill lines are connected in parallel within the magnet end volume to provide a single point of connection. Liquid must be fed into the heat exchanger from the up-hill end and vapour must be pumped from the down-hill end. Since magnets may be installed with either end as the up- or down-hill end, provision is made in the magnet and cryostat to allow operation with either slope by making appropriate connections at the time of installation.

5.3 EXPECTED STATIC HEAT LOAD

The expected static and total heat loads in each magnet at the various operating temperatures are summarised in Table 5.2[14]. Static heat loads due to conduction through the support posts, cold-warm transition and instrumentation feedthroughs, and thermal radiation to the heat shields and magnet are included, as are heat loads due to the QQS and jumpers. The total heat loads are the sum of static and dynamic heating, where the sources of the latter include synchrotron radiation, image currents, beam-gas scattering, photoelectrons, and secondary particles from collisions at the IPs. Further details of the heat loads and their sources are presented in [12] and [14].

5.4 MAXIMUM PRESSURE

The magnets are designed for routine operation up to a pressure of 20 bar. Each magnet undergoes a test to 25% higher pressure, 25 bar.

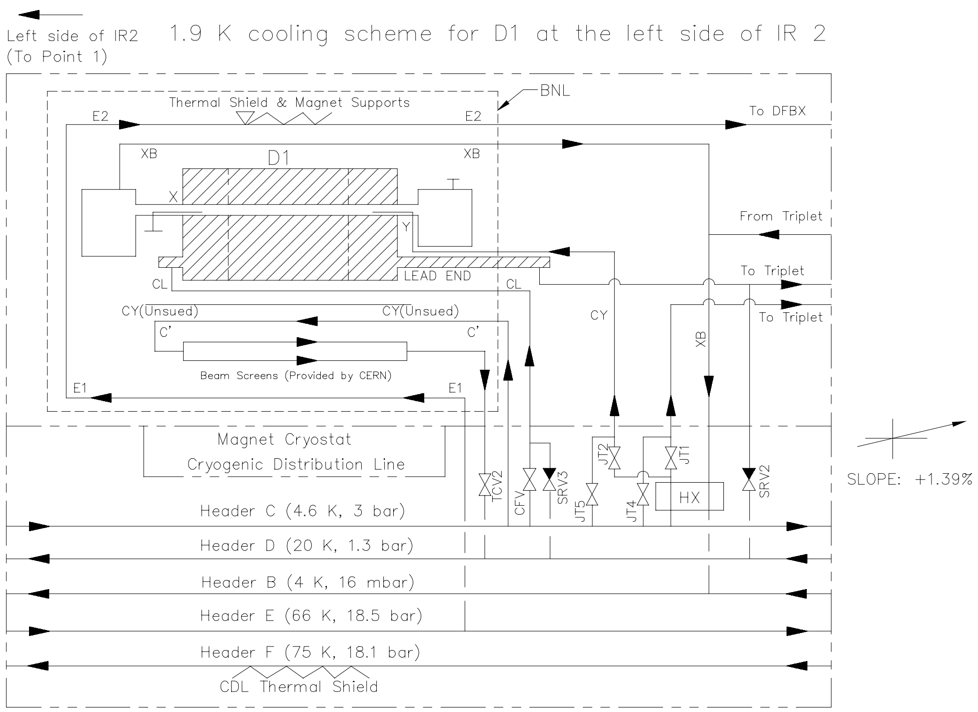

Figure 5.1 1.9 K cooling scheme for D1 at the left side of IR2. Only the section within the box labelled "BNL" is within the scope of this specification.

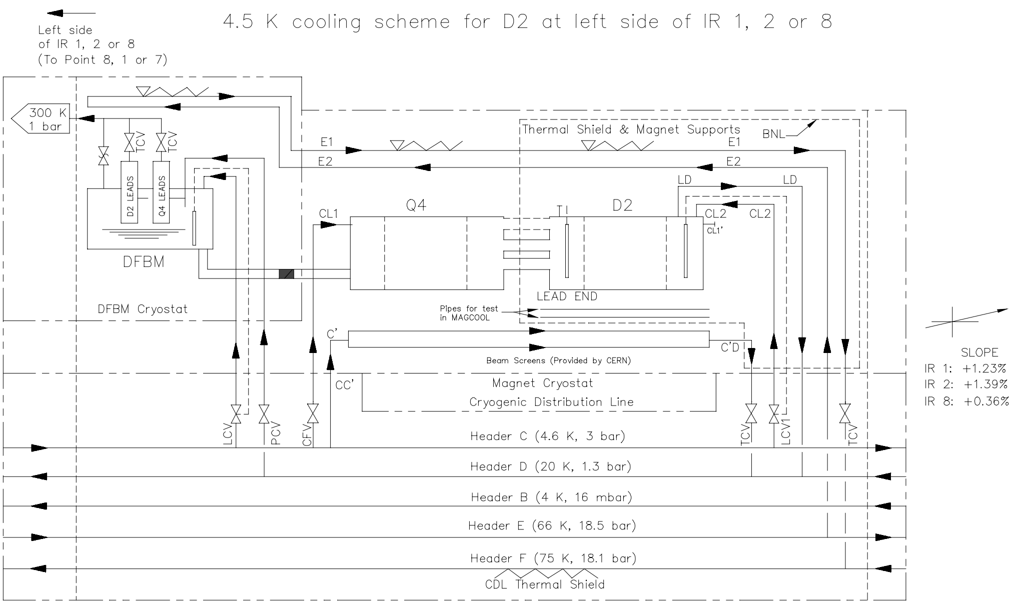

Figure 5.2 4.5 K cooling scheme for D2 at the left side of IR 1, 2 or 8. Only the section within the box labelled "BNL" is within the scope of this specification.

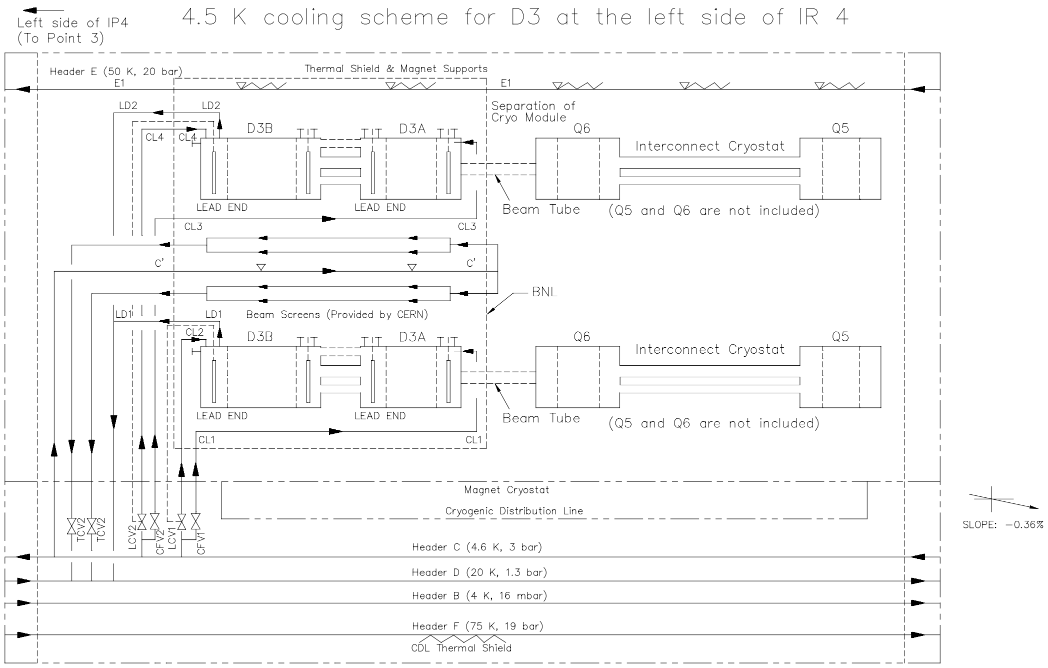

Figure 5.3 4.5 K cooling scheme for D3 at the left side of IR 4. Only the section within the box labelled "BNL" is within the scope of this specification.

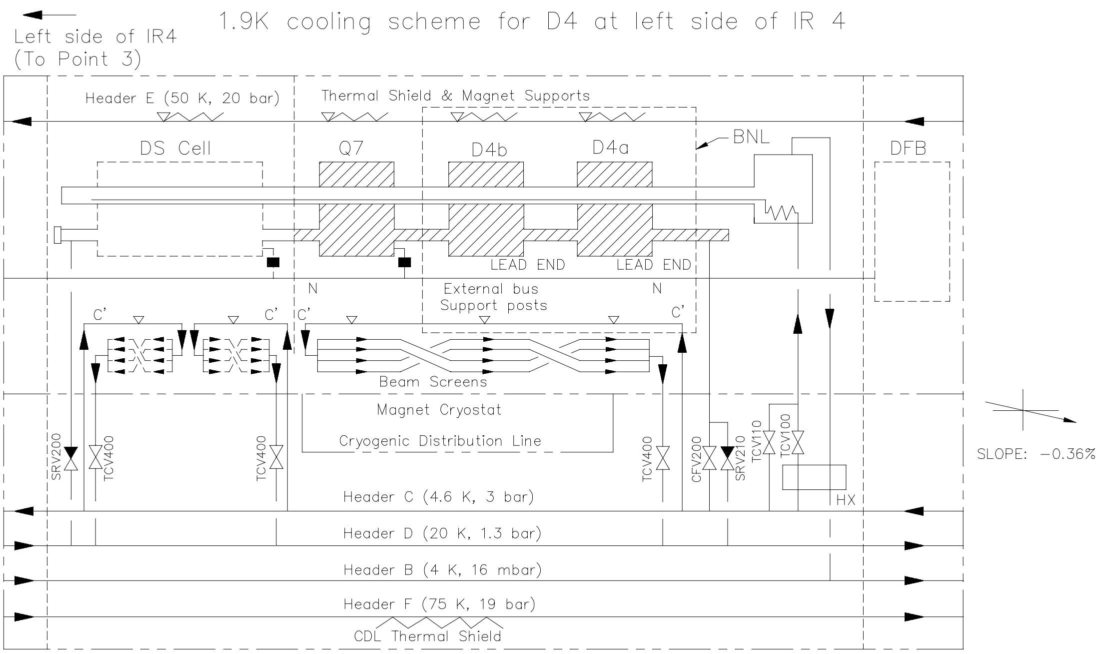

Figure 5.4 1.9 K cooling scheme for D4 at the left side of IR 4. Only the section within the box labelled "BNL" is within the scope of this specification.

Table 5.2a Expected static heat load for each magnet.

	Heat Shield 50 – 75 K	Bm Screen & Supports 4.5 – 20 K	Cold Mass 4.5 K	Cold Mass 1.9 K
D1	23.7	0.11	-	5.58
D2 – IP1 & 5	56.2	2.94	6.91	-
D2 – IP2 & 8	56.2	2.94	7.53	-
D3	56.5	2.94	6.03	-
D4	56.9	2.81	-	3.58

Table 5.3b Expected total heat load for each magnet: nominal luminosity.

	Heat Shield 50 – 75 K	Bm Screen & Supports 4.5 – 20 K	Cold Mass 4.5 K	Cold Mass 1.9 K
D1 – IP2	23.7	5.9	-	6.4(1)
D1 – IP8	23.7	5.9	-	7.7(1)
D2 – IP1 & 5	56.2	6.9	17.4	-
D2 – IP2	56.2	6.3	8.2	-
D2 – IP8	56.2	6.3	18.7	-
D3	56.5	10.6	6.7	-
D4	56.9	10.5	-	4.3

Table 5.4c Expected total heat load for each magnet: ultimate luminosity(2).

	Heat Shield 50 – 75 K	Bm Screen & Supports 4.5 – 20 K	Cold Mass 4.5 K	Cold Mass 1.9 K
D1 – IP2	23.7	16.6	-	6.4(1)
D1 – IP8	23.7	16.6	-	7.8(1)
D2 – IP1 & 5	56.2	13.0	32.2	-
D2 – IP2	56.2	11.6	8.2	-
D2 – IP8	56.2	11.6	18.7	-
D3	56.5	22.4	6.8	-
D4	56.9	22.7	-	4.3

(1) The 4.5-20K and 1.9K dynamic heat loads for D1 assume an actively cooled beam screen. If a passively cooled beam screen is used then the expected heat load to 1.9K would be increased by 5.8 W at nominal luminosity and 16.5 W at ultimate luminosity, and the heat load to 4.5-20K would be reduced by the same amounts.

(2) Heat loads due to secondary particles at IP2 and IP8 do not change between nominal and ultimate luminosity cases, as the luminosity at these points is limited by the requirements of the experiments.

5.5 COOLDOWN AND WARMUP REQUIREMENTS

In order to avoid excessive thermal stresses in magnet components such as the beam tube and the stainless steel shell at the ends, which can occur if a magnet is cooled too rapidly, a maximum thermal gradient over the length of the magnet of 70 K is specified. Upon warm-up, coil prestress may be lost if too high temperatures are reached in the superconducting coils. Tests at Brookhaven have established a maximum magnet temperature of 37°C as a safe upper limit.

5.6 INSTRUMENTATION REQUIREMENTS

A small number of cryogenic measuring devices are installed on or in each magnet to allow for measurement and control of the cooldown, steady state operation, and warm-up of the magnets. The installed instrumentation is summarised in Table 5.3. In all cases redundant instrumentation is provided.

Table 5.5 Cryogenic instrumentation installed in each cold mass. Some additional level probes not counted in this table may be installed in the magnets to facilitate testing.

Magnet	*Device*	*Location*	*Number*
D1	Resistance Thermometer	Magnet yoke, near center	2
	Warm-up Heater	Lead end volume	2
D2	Resistance Thermometer	Magnet yoke, near center	2
	Liquid Level Probe	Non-lead end volume	2
	Warm-up Heater	Lead end volume	2
D3a, each CM	Resistance Thermometer	Magnet yoke, near center	2
	Liquid Level Probe	Both end volumes	4
	Warm-up Heater	Lead end volume	2
D3b, each CM	Resistance Thermometer	Magnet yoke, near center	2
	Liquid Level Probe	Both end volumes	4
	Warm-up Heater	Lead end volume	2
D4a	Resistance Thermometer	Magnet yoke near center,	2
	Warm-up Heater	Lead end volume	2
D4b	Warm-up Heater	Lead end volume	2

6. BEAM VACUUM REQUIREMENTS

6.1 COLD BORE

The magnets include cold beam tubes with dimensions given in Table 6.1. Two sizes are required. Magnets that operate at 4.5 K need a larger gap between the beam tube and the coil for effective cooling by the liquid helium [15]. For magnets that require a maximum aperture, a smaller gap can be allowed if the magnets are cooled by superfluid helium (1.9 K).

The tubes are centred inside the coils: horizontally with G-10 bumpers spaced axially at regular intervals, vertically by the collars or by the phenolic spacers in the case of the 1-in-1 magnets. The gap between tube and coil defines a helium buffer space. The tube is seamless, 316 LN stainless steel and is wrapped with 25 μm thick polyimide film with 66% overlay. This provides 75 μm of insulation, which is tested for integrity to ground at 5 kV.

6.2 BEAM SCREEN

Actively cooled beam screens will be installed into all magnets after delivery to CERN. Experimental requirements at IR2 require the maximum possible physical aperture at the end of the D1 magnets farther from the IP. This may require that the beam screen in these magnets have a larger inner diameter, leaving open the possibility that they will be passively cooled only.

Table 6.1 Dipole cold bore parameters

Item	*Units*	*D1*	*D2, D3, D4*
Beam Tube		Enlarged tube	Standard tube
Outer diameter	mm	78.0 ± 0.4	73.0 ± 0.4
Outer diameter inc. insulation	mm	78.15 ± 0.4	73.15 ± 0.4
Wall thickness	mm	2.0 ± 0.2	2.0 ± 0.2
Inner diameter, nominal	mm	74	69
Weight, nominal	kg	38	34
Beam tube-coil radial gap, nominal	mm	0.9	3.4
Test voltage	kV	5	5
Material		SS 316 LN	SS 316 LN
Insulation thickness	mm	0.075	0.075
Copper coating required		No	No

7. RADIATION REQUIREMENTS

All materials used in the construction of the beam separation dipoles must be able to withstand the expected integrated radiation dose during the 20 year lifetime of the LHC. The integrated dose depends strongly on the location of the magnet, and varies strongly within the individual magnet. Table 7.1 summarises the maximum integrated dose expected to be deposited in the coils of each magnet.

Table 7.1 Expected maximum integrated radiation dose in the magnet coils during 20 years of operation

Name	*Location*	*Dose, Gy*	*Reference*
D1	IR2	4×10^2	[16]
D1	IR8	5×10^6	[17]
D2	IR1, IR5	2×10^6	[17]
D2	IR2	2×10^4	[16]
D2	IR8	4×10^7	[17]
D3, D4	IR4	To be determined	

8. RELIABILITY REQUIREMENTS

8.1 LIFETIME

All the beam separation dipoles will be required to operate during the entire expected 20 year lifetime of the LHC. Considerations include integrated radiation dose (see section 7), number of thermal cycles, number of excitation cycles and number of quenches. The expected lifetime of LHC and the expected number of cycles of each type are specified in [18] and summarised in Table 8.1

Table 8.1 Required lifetime parameters.

Item	*Value*
LHC Lifetime (years)	20
Number of Thermal Cycles	25
Number of Powering Cycles	12,000
Number of Quenches	10

8.2 SPARES

One fully tested spare magnet of each type (D1, D2, D3a, D3b, D4a, and D4b) will be built and delivered to CERN. Each spare will contain all features necessary to allow it to be installed in any location, together with a kit of field added parts required to customise it to any particular location into which it may be installed.

8.3 REPAIR AND REPLACEMENT

A package of documentation including construction drawings, travellers, discrepancy reports, measurements and performance results will be included with each magnet. No tooling nor spare parts are planned for delivery. If needed, minor repairs can be effected at CERN. If an in-service magnet fails, it can be replaced with one of the spares at CERN by CERN staff, which is responsible for installation.

9. SHIPPING AND INSTALLATION REQUIREMENTS

9.1 SHIPPING REQUIREMENTS

Once construction and testing of the magnets is complete, they will be shipped to CERN for installation into the LHC. To prepare them for transit, steel support posts and end restraining frames will be installed to protect the cold mass support posts from damage. The magnets will be sealed and filled with dry nitrogen so that moisture cannot penetrate the cryostat or cold mass. Each magnet will be mounted on a shock-absorbing frame and then placed into a standard 40-foot-long shipping container. This container will be transported by truck to a shipping terminal, then by ocean freight to a terminal in Europe, then by truck to CERN. The frames will be returned to BNL for reuse. All magnet components must be designed such that the shipped assembly will fit within a standard 40 foot shipping container.

9.2 INSTALLATION REQUIREMENTS

A magnet is lifted with suitable slings fastened around the cryostat cradles, where the magnet's weight is concentrated. In lifting or transporting a magnet after the shipping restraints have been removed, abrupt motions that could apply large g-forces or lateral forces to the magnet must be avoided. The weights of the various magnets are given in Table 9.1.

Table 9.1 Magnet Weights

Magnet	Weight, kg	Method
D1	4730	weighed
D2	22700	estimated
D3	10500	estimated
D4	22700	estimated

10. ALIGNMENT REQUIREMENTS

CERN-type holders for Taylor-Hobson spherical targets [19] will be installed on the cryostat of each magnet. These features and their locations will be finalized in the Interface Specification. The position of the magnetic axis will be determined relative to the Taylor-Hobson spherical targets on that magnet, and this information will be transmitted to CERN for use during installation. The required alignment accuracy of each component will be the subject of a separate engineering specification.

11. CERN PROVIDED PARTS

11.1 COMPONENTS PROVIDED BY CERN TO BNL

CERN has agreed to provide to BNL a number of components which are of a common design with the main magnets. These items are listed in Table 11.1.

Table 11.1 Components to be provided by CERN to BNL.

Item	*Magnets*	*Quantity*
End Covers	D2, D4	30
Cold Bore Tubes - 78 mm OD	D1	10
Cold Bore Tubes - 73 mm OD	D2, D3, D4	50
Heat Exchanger Tubes – 58 mm OD	D4	6
Cryostat Cradle Casting	D2, D3, D4	63
Heat Shield Extrusion (length - 11000 mm)	D2, D3, D4	21
Dipole Support Posts	D2, D3, D4	63
Support Post Radiation Discs	D2, D3, D4	126
Dipole Bus Assembly (length - 11000 mm)	D4	12
Quadrupole Bus Assembly (length – 11000 mm)	D4	12
Superconductor for 11 kA Lyre Assembly	D4	TBD
Cold Mass Temperature Sensors	D1, D2, D3, D4	70
Warm-up Heaters	D1, D2, D3, D4	70

11.2 COMPONENTS INSTALLED AT CERN

Several components must be installed in or attached to these magnets after delivery to CERN and prior to installation in LHC. All magnets must have beam screens installed. Cryogenic service modules (QQS) must be assembled onto the left end of the D3b on the left side of IR4, onto the left end of the D3a on the right side of IR4, onto the right end of D4a on the left side of IR4, and onto the left end of D4a on the right side of IR4.

12. LIST OF INTERFACES

Table 12.1 gives a high level summary of the interfaces between the different beam separation dipoles and other equipment.

Table 12.1 Interfaces for each separation dipole. In addition, each dipole will have interfaces with the tunnel floor and the alignment system

Magnet	*IP*	*Toward IP*	*Away From IP*
D1	2, 8	DFBX	CWT[(2)]
D2	1, 2, 5, 8	QRL[(1)], CWT[(2)]	Q4
D3a	4	Q6	D3b
D3b	4	D3a	QQS[(3)], DFBA
D4a	4	QQS[(3)], DFBA	D4b
D4b	4	D4a	Q7

(1) The D2 cryostat includes a small technical service module (mini-QQS) to interface with the ring distribution line (QRL).

(2) CWT – cold to warm transition.

(3) D3b and D4a will have cryogenic service modules (QQS) mounted to the indicated ends of the magnets at CERN prior to installation.

13. REFERENCES

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